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A review of energy storage systems in microgrids with wind turbines

Abdorreza Rabiee [a,*], Hossein Khorramdel [b], Jamshid Aghaei [c]

[a] Department of Electrical Engineering, Faculty of Technology and Engineering, Shahrekord University, Shahrekord, Iran
[b] Department of Electrical Engineering, Dezful branch, Islamic Azad University, Dezful, Iran
[c] Department of Electrical and Electronics Engineering, Shiraz University of Technology, Shiraz, Iran

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ABSTRACT

Installing energy storage systems (ESS) for wind turbines power can bring many benefits to both power grids and wind power developers. Considering the stochastic nature of wind, electric power generated by wind turbines is highly erratic and may affect both the power quality and the planning of power systems. ESS should play a key role in wind power applications by controlling wind power plants output and providing ancillary services to the power system, and therefore, enabling an increased penetration of wind power in the system. This article deals with the review of various storage systems for wind power applications. The main objectives of the article are the introduction of the operating principles, the presentation of the main characteristics of energy storage systems suitable for stationary applications, and the definition and discussion of potential ESS applications in wind power, according to an extensive literature review.

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* Corresponding author.
E-mail addresses: rabiee@iust.ac.ir (A. Rabiee), hossein.khorramdel@gmail.com (H. Khorramdel), aghaei@sutech.ac.ir (J. Aghaei).

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1. Introduction

Microgrid is an active distribution network which includes both loads and Distributed Generations (DGs) with different reactive power control strategies and can operate in grid- connected or stand-alone mode [1,2]. Wind energy is one of the fastest growing sources of electricity at present. Electric power, generated by wind turbines, is highly erratic; therefore, the wind power penetration in power systems can lead to problems related system operation and the planning of power systems [3]. In this paper, ESS play a key role in wind power applications by controlling wind power plant output and providing ancillary services to the power system and thus, enabling an increased penetration of wind power in the system. In addition, a revision of specific, worldwide ESS examples for renewable energy applications is detailed in [4]. Accordingly, this article focuses on two main objectives, first the introduction of operating principles and the main characteristics of several storage systems suitable for stationary applications, and secondly, the definition and discussion of potential ESS applications in wind power. The classification of potential ESS applications has been performed under full power duration of the storage criteria in each case. Thus, applications where ESS are required to inject or absorb power for less than a minut[illegible] power smoothing of wind turbines; or long-term storage applications, such as those related to load following or seasonal storage, have been considered [5]. Increasing wind power integration is desirable, [illegible] maintaining the grid stable operation is also a m[illegible] to mitigate wind power intermittency, load mismatch, and negative impacts on grid voltage stability are some key problems [illegible] solv[illegible] potential candidate solution for the identified problems [illegible] ESS to store wind power at the time of surplus and re-dispatch[illegible] appropriately. In this way, it is possible to increase [illegible] match between wind farms power production and grid demand, as [illegible] as to mitigate the voltage problems [6].

2. Energy storage systems

Electrical energy can be converted to many different forms for storage [7]:

- Gravitational potential energy with water reservoirs,
- Compressed air,
- Electrochemical energy in batteries and flow batteries,
- Chemical energy in fuel cells,
- Kinetic energy in flywheels,
- Magnetic field in inductors,
- Electric field in capacitors.

In this section, a review of several available systems of energy storage that can be used for wind power applications is evaluated. Among other aspects, the operating principles, the main components and the most relevant characteristics of each system are detailed.

2.1. Pumped hydro storage (PHS)

PHS is a large scale energy storage system. Its operating principle is based on managing the gravitational potential energy of water, by pumping it from a lower reservoir to an upper reservoir during periods of low power demand. When the power demand is high, water flows from the upper reservoir to the lower reservoir, activating the turbines to generate electricity. [illegible] energy stored is proportional to the water volume [illegible] the upper reservoir and the height of the waterfall. According to [33], the use of PHS can be divided into 24 h time-scale applications and applications involving more prolonged energy storage in time [illegible] several days' hydro-storage capacity [illegible] many [illegible] global[illegible] kind one applications, the potential is around 1[illegible] GW, and for type two, 1454 GW. This system is the most [illegible] for high-power applications [5]. This installation was commissioned in 1[illegible]. The system is capable of moving from [illegible] 1320 MW [illegible] injection in 12 s by means of managing [illegible] motor-generators of 330 MW activated by reversible Francis water turbines installed in Europe's largest man-made cav[illegible] general, the life time of PHS installations is around [illegible]0 years, with an acceptable round trip efficiency of 65–75% [8].

2.2. Compressed air energy storage (CAES)

CAES systems are based on conventional gas turbine technology. [illegible]is kind of system, the energy is stored in form of compressed air in [illegible] underground storage cavern. When energy is required to be injected into the grid, the compressed air is drawn from the storage cavern, heated and then expanded in a set of high and low pressure turbines which convert most of the energy of the compressed air into rotational kinetic energy. The air is additionally mixed with natural gas and combusted. While the turbines are connected to electrical generators in order to obtain electrical energy, the turbine exhaust is used to heat the cavern air. The structure of this system is shown in Fig. 1 [5]. Only two plants have been constructed in the world so far; in Germany (290 MW) and the other in the USA (110 MW) [5]. As its name suggests, the air is adiabatically compressed and then pumped into an underground cavern. The key parts of this system are the heat exchangers, which are quite very expensive. The life time of CAES installations is approximately 40 years, with an energy efficiency of 71% [12].

2.3. Battery energy storage system (BESS)

Batteries are one of the most used energy storage technologies available on the market. The energy is stored in the form of electrochemical energy, in a set of multiple cells, connected in series or in parallel or both, in order to obtain the desired voltage and capacity. Each cell consists of two conductor electrodes and an electrolyte, placed together in a special, sealed container and connected to an external source or load [34]. The electrolyte enables the exchange of ions between the two electrodes, while the electrons flow through the external circuit. According to [18], BESS comprises batteries, the Control and Power Conditioning System (C-PCS) and the rest of the plant, which is in charge of providing good protection for the entire system (see Fig. 2 [18]). Many types of batteries are now mature technologies. In fact, research activities involving lead–acid batteries have been conducted for over 140 years.

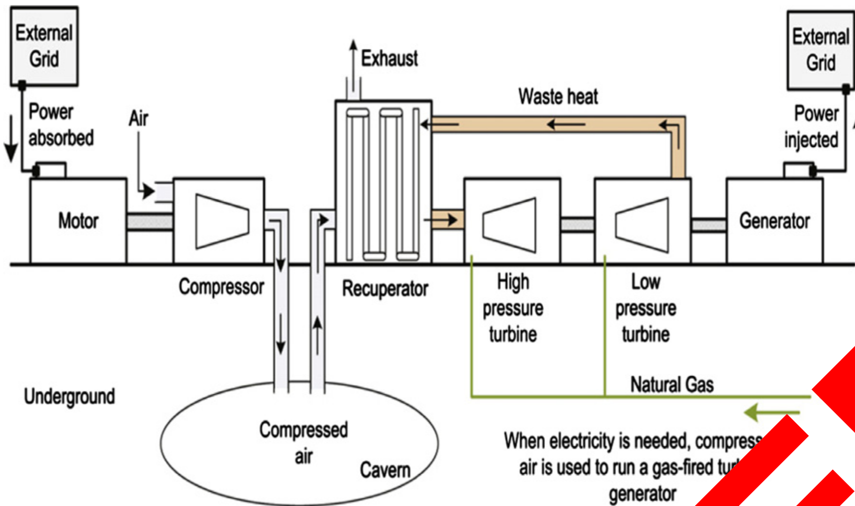
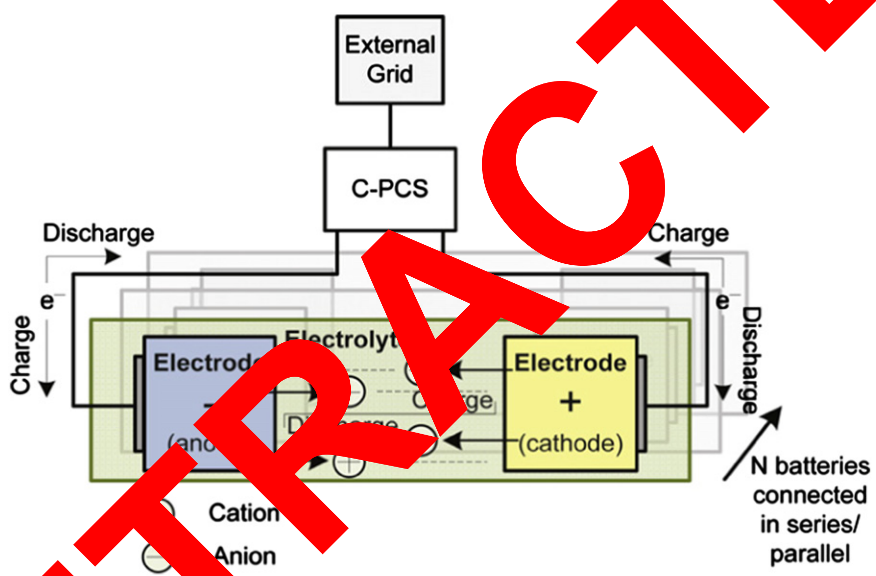


Fig. 1. System description of compressed air energy stora[illegible]



Fig[illegible]peration principle of Battery Energy Storage System.

2.3.1. Lead–acid battery[illegible]

The lead–aci[illegible]tery i[illegible] most [illegible]ture kind of battery. It is made up of s[illegible]s, imm[illegible] a dilute solution of sulfuric acid (H_2SO[illegible]s an e[illegible]trolyte. T[illegible] positive electrode of each cell is compo[illegible]f lea[illegible](PbO_2), while the negative electrode is sponge le[illegible]). Durin[illegible]ischarge, both electrodes are converted into lea[illegible]lphate ($PbSO_4$). During the charge cycle, both electrodes return [illegible]heir initial state. There are two major kinds of lead–acid batte[illegible]s: flooded batteries and valve-regulated batteries. The life time of the system is approximately 5–15 years with an energy efficiency of 75–80% [35].

2.3.2. Nickel–cadmium battery (Ni–Cd)

Development of this kind of alkaline rechargeable batteries has been carried out since 1950. This has helped to make them a well-established system in the market place. The main components of Ni–Cd batteries are nickel species and cadmium species as the positive and negative electrodes' active materials, respectively, and aqueous alkali solution as the electrolyte [36]. During the discharge cycle, $Ni(OH)_2$ is the active material of the positive electrode, and $Cd(OH)_2$ is the active material of the negative electrode. During the charge cycle, NiOOH is the active material of the positive electrode, and metallic Cd the active material of the negative electrode. The alkaline solution KOH acts as the electrolyte. The Ni–Cd battery has suitable characteristics with respect to its long cycle life (more than 3500 cycles), combined with low maintenance requirements [11]. Nevertheless, its cycle life is highly dependent on the depth of discharge (DD). It can reach more than 50,000 cycles at 10% of DD.

2.3.3. Sodium–sulphur battery (NaS)

Besides being a relatively recent system, NaS batteries are one of the most promising options for high power energy storage applications. The anode of this kind of battery is made of sodium (Na), while the cathode is made of sulphur (S). Ceramic Beta–$Al2O_3$ acts as both the electrolyte and the separator simultaneously [19]. During the discharge cycle, the metallic anodic material (sodium) is oxidized and releases Na^+ ions, while the cathodic material is reduced and releases S^{-2} sulphur anions. The electrolyte enables the transfer of sodium ions to the cathode,

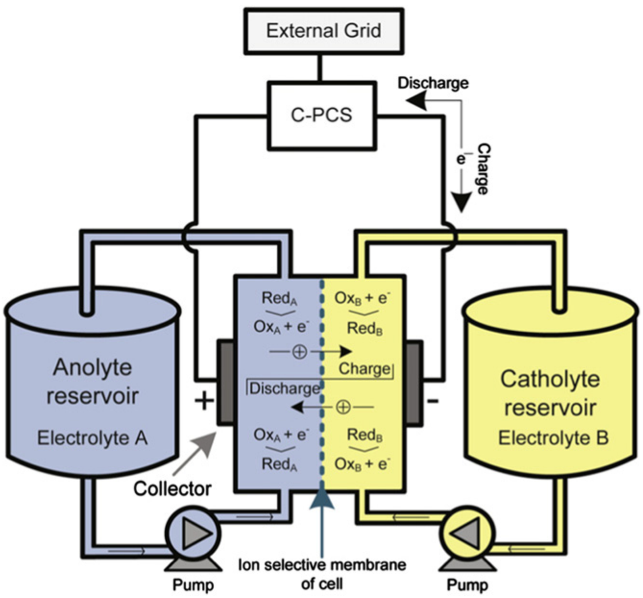


Fig. 3. Operation principle of Flow battery energy storage system.

where they combine with sulphur anions and produce sodium polysulphide NaS_x. During the charge cycle, the opposite reaction occurs. An important feature of this type of battery is its high temperature operation, around 350 °C. One of the largest manufacturers of NaS batteries is the Japanese company NGK insulators [27,38]. The energy density and the energy efficiency of this kind of batteries are very high, 151 kW h/m^3 and 85%, respectively. Additional important features of NaS batteries are no self-discharge, low maintenance and their 99% recyclability.

2.3.4. Lithium-ion battery (Li-ion)

Li-ion batteries are widely used in small applications such as mobile phones and portable electronic devices [illegible]e annual production gross is around 2 billion cells [illegible]. In addition, this kind of batteries attracts much interest in the field of material technology and others, in order to obtain high power devices for applications like electric vehicles and stationary energy storage. The operation of Li-ion batteries is based on the electrochemical reactions between positive lithium ions (Li^+) with anolytic and catholytic active materials [illegible]. The cells of Li-ion batteries are made of anolytic and catholytic plates filled with liquid electrolyte material. The electrode areas are delimited by a porous separator of polyethylene or polypropylene, which allows the transit of lithium ions. During the charge cycle, Li^+ flows from the positive electrode made of $LiCoO_2$, to the graphite sheets of the negative electrode. The discharge cycle consists of the reverse process. Since the performance and the range size of the battery are strongly related to the active materials of the electrodes and the electrolyte, there is a tremendous amount of research in the field of material technology nowadays [39]. As important features of Li-ion batteries are time constants (understood here as the time to reach 90% of the rated power of the battery) around 200 ms, with a relatively high round trip efficiency of 78% within 3500 cycles, have been reported [30].

2.4. Flow battery energy storage system (FBESS)

Flow batteries are a relatively new system. Their operating principle is based on reversible electrochemical reactions that occur in a set of cells connected in series, parallel or both, in order to achieve the desired voltage level. Unlike conventional batteries, two different aqueous electrolytic solutions are contained in separate tanks. During the normal operation of the battery, these aqueous solutions are pumped through the electrochemical cell where the reactions occur [17,40]. Three kinds of commercially available flow batteries are considered in this article: Vanadium Redox Battery (VRB), Zinc Bromine Battery (ZBB) and Polysulphide Bromide Battery (PSB). Since their operation is based on reduction and oxidation reactions of the electrolyte solutions, these kinds of batteries are also called redox flow batteries. Their operating principle is presented in Fig. 3 [40]. As shown, during the charge process, the electrolyte A is oxidized at the anode, while the electrolyte B is reduced at the cathode. The discharge cycle consists of the reverse process. One of the major advantages of flow batteries is that their energy capacity is easily scalable, since it depends on the volume of the stored electrolyte. This leads to lower installation costs the larger the system is [37]. In this sense, the ZBB presents worse performance than a PSB and VRB, since a third pump is required for the recirculation of bromine complexes. Other interesting features of flow batteries are their ability to be completely discharged without any damage, and their very low self-discharge, since the electrolytes are stored in separate [illegible] tanks. Thereby, redox flow batteries result as systems with a long life and low maintenance, able to store energy over long periods of time.

2.4.1. Vanadium redox flow battery (VRB)

The VRB stores energy in two tanks, an anolytic and catholytic reservoir, and containing sulphuric acid solutions. In the anolytic reservoir, V^{2+}/V^{3+} are used as electrolytes, while the electrolytes [illegible] are used in the catholytic reservoir [13,23,24]. When an electrochemical reaction occurs, carbon electrodes [illegible] the electron flow through the load. At the same, the electrical balance is achieved by means of the migration of a hydrogen ion through the membrane which separates the two electrolytes. Since the products of chemical reactions remain dissolved in the electrolytes, the reverse process leads solutions to their initial state. The system life is about 15–20 years, with more than 1000 charge and discharge cycles at 100% of DD [16].

2.4.2. Zinc–bromine flow battery (ZBB)

In ZBBs, two aqueous solutions, based on Zn and Br store in separate tanks, flow through electrolytic cells where the reversible electrochemical reactions are produced. During the discharge process, bromide ions Br^- are converted to bromine Br^{-3}, in the positive electrode, which reacts with other organic amines and creates thick bromine oil that sinks to the bottom of the tank. Meanwhile, in the negative electrode, positive zinc ions Zn^{2+} are converted to metallic Zn. Reverse reactions to those described are carried out during the charge process of the battery. Cell electrodes are composed of carbon–plastic composite and are separated by means of a micro-porous polyolefin membrane [13,14]. Large amounts of energy can be stored for long periods of time due to virtually no self-discharge of the battery [26]. Other important features of this system are high energy efficiency of 75–85% [17].

2.4.3. Polysulphide–bromide flow battery (PSB)

The operation of PSBs, also called regenerative fuel cells or Regenesys, are based on the electrochemical reactions between two salt-based electrolytes: sodium bromide (NaBr) and sodium polysulphide (Na_2S_x). The electrolytes are separated by a polymer membrane which only allows the interchange of positive sodium ions [13,18,37,40]. During the charge cycle, bromide ions (Br^-) are transformed into tribromide ions (Br^{-3}) in the positive electrode of the cell. In the negative electrode, dissolved sodium particles (S_2^{-4}) in the polysulphide electrolyte are reduced to

sulphide ions (S_2^{-2}). The discharge cycle consists of the reverse process. These systems built the larger system based on this battery type in 2003. The energy efficiency of the system is 75%, with a relatively long life, more than 15 years.

2.5. Hydrogen-based energy storage system (HESS)

When hydrogen is produced from wind power plants, it can be stored in order to be used directly in fuel cells, or transported to users through pipelines to produce electricity [42]. When hydrogen is stored, the system used is known as Regenerative Fuel Cell (RFC) [10]. As shown in Fig. 4 [44], it is composed of the following components: a water electrolyzer system, a fuel cell system, a hydrogen storage and a power conversion system. This technology is responsible for carrying out the electrochemical transformations in order to store energy in the form of hydrogen and inject it as electricity into the grid, when required. As presented, electrolyzers are important parts of RFCs. By means of these devices, water is electrolytically decomposed into hydrogen and oxygen. There are many kinds of electrolyzers, from common systems such as Alkaline electrolyzers [42], to more modern kinds like Polymer Electrolyte Membrane (PEM) electrolyzers. PEM electrolyzers were invented in 1970, but hydrogen production by means of this kind of technology is currently considerable, reporting production volumes up to 10 N m^3/h [43]. There are many types of fuel cells for stationary and distributed generation purposes [44,45], depending on their electrolytic material. In Fig. 4, the Polymer Electrolyte Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) are detailed. The PEMFC is the most used technology. Its low operation temperature (between 50 and 100 °C), maintenance and corrosion, as its electrolyte is solid, are important characteristics of this type of fuel cell. On the other hand, since the catalytic material is platinum, the cost of the device increases significantly. In addition, the system is affected by hydrogen impurities, which affect its life. Fuel cells are noted for their good dynamic behavior, allowing a quick start-up, even at partial load. No acoustic emissions are noted during their operation and they only discharge water as a product [41]. As they are flow batteries, RFC power and energy capacity are not related characteristics. Finally, notice that one of the major drawbacks of a RFC is its low energy efficiency, about 42%, due to the relatively low energy efficiencies of the fuel cell and the electrolyzer, about 60% and 70%, respectively [22].

2.6. Flywheel energy storage system (FESS)

An FESS is an electromechanical system that stores energy in form of kinetic energy. A mass rotates on two magnetic bearings in order to decrease friction at high speed, coupled with an electric machine. The entire structure is placed in a vacuum to reduce wind shear [21,37,46]. The scheme of the system is presented in Fig. 5 [47]. Energy is transferred to the flywheel when the machine operates as a motor (the flywheel accelerates), charging the energy storage device. The FESS is discharged when the electric machine regenerates through the drive (slowing the flywheel). In fact, the energy stored by the flywheel is dependent on the square of the rotating speed and its inertia. In general, flywheels can be classified as low speed and high speed devices. The first operates at revolutions per minute (rpm), measured in thousands (this class of flywheel uses steel as the main structural material in the rotor), while the latter operates at rpm measured in tens of thousands (this class of flywheel uses a rotor made of an

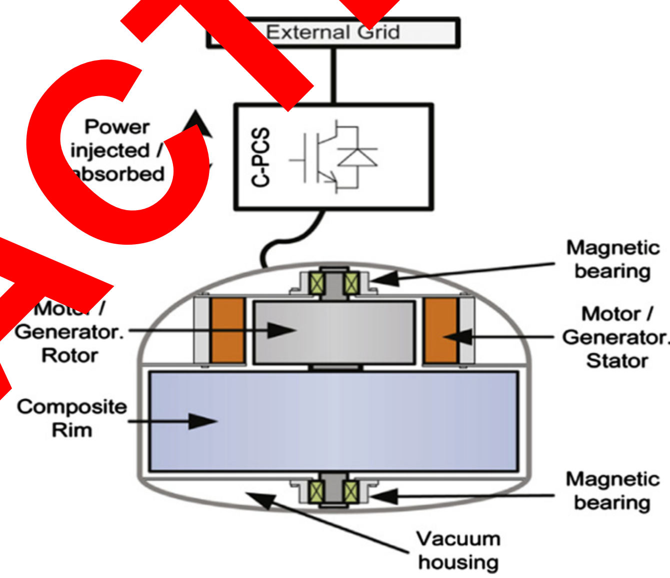


Fig. 5. Topology of Flywheel Energy Storag System.

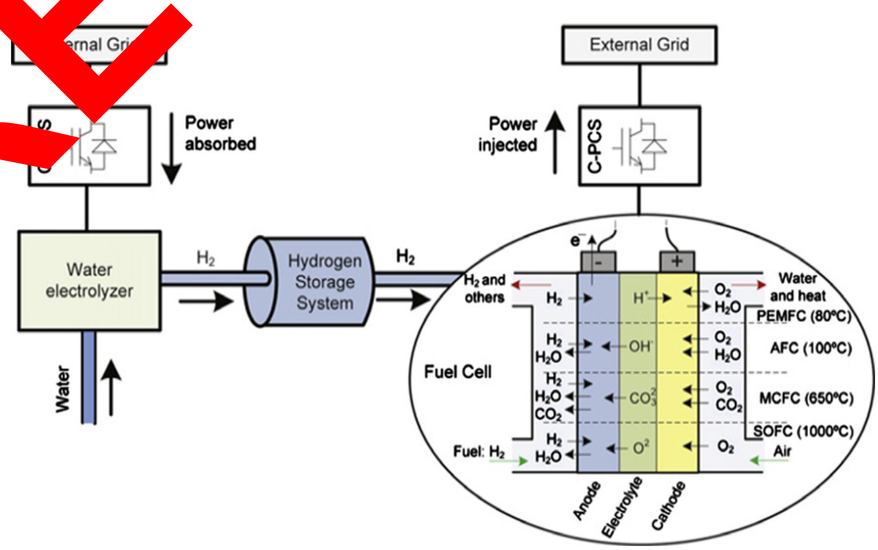


Fig. 4. Topology of regenerative fuel cell.

advanced composite material, such as carbon-fiber or graphite [21,47]). A FESS presents suitable features regarding high efficiency (around 90% at rated power), long cycling life, wide operating temperature range, freedom from depth-of-discharge effects, higher power and higher energy density [20,37,46,48].

2.7. Superconducting magnetic energy storage (SMES)

The SMES system is a relatively recent technology. The first system based on this technology was built in 1970 [20]. Its operation is based on storing energy in a magnetic field, which is created by a DC current through a large superconducting coil at a cryogenic temperature. The energy stored is calculated as the product of the self inductance of the coil and the square of the current flowing through it [31]. Thus, the characterization of the coil has a central role in the system design. Depending on the system operating temperatures, superconducting coils can be classified as: High Temperature Coils (HTS), which work at temperatures around 70 K, and Low Temperature Coils (LTS), a more mature system, with working temperatures around 5 K. A balance between cost and system requirements determines the technology used. The maximum current that can flow through the superconductor is temperature dependent. Indeed, the lower the operating temperatures, the higher the operating currents that can be achieved. Therefore, higher energy densities than those of flywheels and conventional batteries can be obtained. These systems have very high energy efficiencies up to 90% [31]. Two different kinds of power converters are considered, the VSC and the CSC [31]. Even though the active and reactive power can be properly controlled with both power electronics-base[illegible] verters, a reactive power management with a very low o[illegible] zero current in the coil is only possible with VSC. Undoubte[illegible] a defining feature of these systems is their ability to inject or ab[illegible] large amounts of energy in a very short time. Th[illegible]y capa[illegible] of these systems ranges from 100 kW to 10 M[illegible] and [illegible] possib[illegible] to inject their rated power only for a fe[illegible]nutes [illegible]ore being discharged [20,31].

2.8. Super capacitor energy stora[illegible]tem

Super capacitors are als[illegible] known as [illegible] capacitors or double layer capacitors. Like b[illegible]ries, super ca[illegible]tors are based on electrochemical cells [illegible]ch co[illegible]in two con[illegible]ctor electrodes, an electrolyte and a porous membrane whereby ion transit between the two electrodes is permitted. In fact, this structure creates two capacitors (due to both interfaces, electrolyte – negative electrode and electrolyte – positive electrode), and for this reason, they are called double-layer capacitors. The energy stored in the capacitors is directly proportional to their capacity and the square of the voltage between the terminals of the electrochemical cell, while the capacity is proportional to the electrode-surface area and inversely proportional to the distance between the electrodes. Due to their low-cell voltage (about 3–4 V), the desired voltage and capacity of the super capacitor are achieved by the series and parallel connection of a set of cells [7]. [illegible]tructure of a system based on a super capacitor is sh[illegible] 6 [52]. Unlike unsymmetrical ones, symmetric[illegible]uper capa[illegible]rs utilize the same material for their positive [illegible]negative e[illegible]trodes. Moreover, further classification c[illegible]be ma[illegible]r electr[illegible]es based upon their materials [50,51].

In fact, activated [illegible]on ele[illegible]odes p[illegible]e capacities from 100 to 1000 times pe[illegible]t v[illegible]e over conventional electrolytic capacitors. Conc[illegible]ing [illegible]ctrolyt[illegible]nce its breakdown voltage limits th[illegible]oltage o[illegible] su[illegible]capacitor cell, the proper choice of i[illegible]terial is v[illegible]portant. In addition, power densities [illegible] tim[illegible]igher than [illegible]atteries can be achieved. These features, combine[illegible]th the high self-discharge of the system (w[illegible]n be 20% o[illegible] rated capacity in 12 h, due to the non [illegible]igible equivalent [illegible]sistance of the contact between the [illegible]ctrolyte and the electrodes [25,52]), define the system as a [illegible]didate fo[illegible]hort time scale applications with short time r[illegible]nses. Ot[illegible] important features of super capacitors are their lo[illegible] than 5×10^4–10^5 cycles with virtually no maintenance [illegible] energy efficiency of about 75–80% [32].

3. Applications of the storage systems in microgrid with wind turbines

This section details the potential applications of ESS in microgrids with wind turbines. Each technical issue, concerning different aspects related with the management of wind power plants and their integration into the electrical network, has been identified and defined according to [3,4,15,28,29].

Fig. 7 shows a typical microgrid equipped with different type of distributed generators, energy storage systems and decentralized controllers for loads and micro power sources. The main role

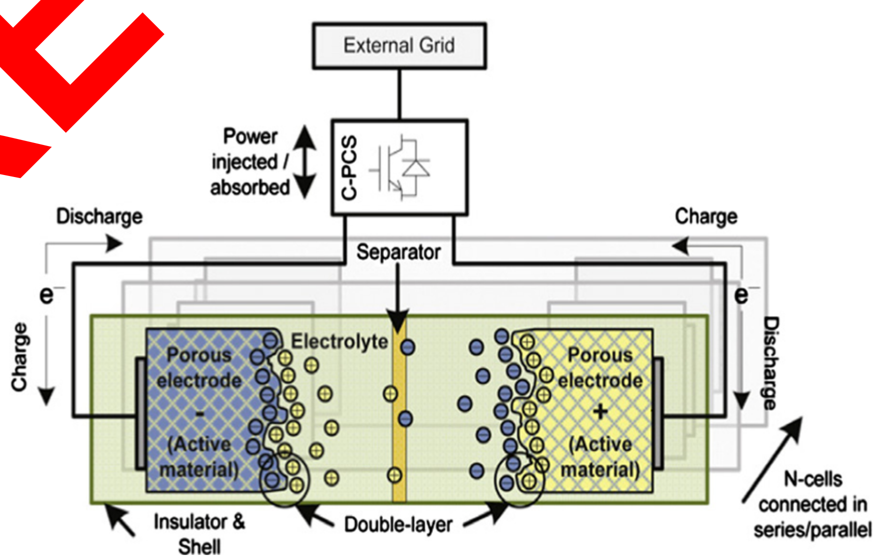


Fig. 6. Energy storage system based on a super capacitor.

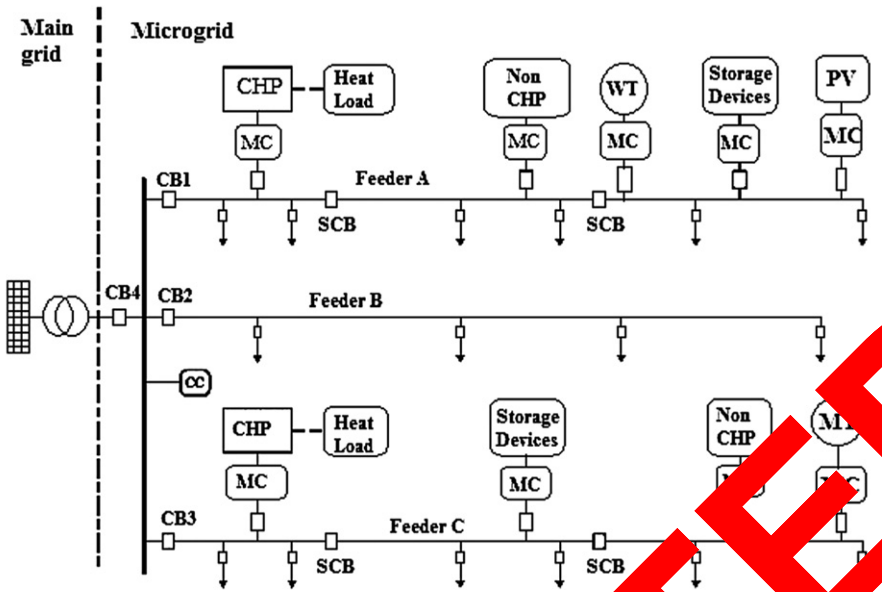


Fig. 7. Typical microgrid.

of MGCC is coordination of micro source controllers (MCs) and Load controllers (LCs) to have a secure, stable, reliable and optimal operation. The interesting point about energy storage systems is injecting the needed power into grid in demand peak hours and absorbing the excess of power in the grid.

3.1. Fluctuation suppression

Fast output fluctuations (in the time range up to a minute) [illegible] the power of wind generators can cause network f[illegible]ency an[illegible] voltage variations, especially in isolated power s[illegible]d thus impairing the power quality [78]. In order to [illegible]gate t[illegible] effects of power fluctuations, an ESS can be us[illegible]tora[illegible] suitable for this application present hig[illegible]amp[illegible] rates [illegible] high cycling capability, since fast po[illegible]modulat[illegible]nd continuous operation are required. Thus[illegible]ries (exclu[illegible]conventional lead–acid batteries), flow[illegible]atte[illegible] and especi[illegible]y short time scale energy storage li[illegible] super cap[illegible]rs, flywheels and SMES are well suited for t[illegible]ervice. A wide[illegible]ccepted solution to mitigate the power f[illegible]uatio[illegible] of a wind [illegible]urbine driving a DFIG is to include a[illegible]S in[illegible] dc link of the back-to-back converters of the machi[illegible]storage[illegible]ice is equipped with a control which i[illegible]cts w[illegible]he tu[illegible]es and other controls in order to opti[illegible]et po[illegible]ered to the external grid by the entire [illegible]em [7[illegible] This is t[illegible]ase presented in [59]: a super capacito[illegible]ecte[illegible]-link of a wind generator through a two-quadra[illegible]c conve[illegible]r. As a wind turbine controller, the C-PCS of each [illegible]ge device receives the set point calculated by the high level co[illegible]ller, and manages the power injection or absorption by mea[illegible] of computing the difference between this signal and the actual active power of the wind generator. Flywheels are also under study for complementation of the dc-link of DFIG wind turbines. In addition to the use of induction machines, permanent magnet and switched reluctance machines are studied for flywheel storage devices [58]. As noted at the beginning of this section, the effects of power fluctuations of wind turbines regarding power quality issues are remarkable, especially in isolated systems. Related to this problem, the combination of storage systems, like flywheels, super capacitors or batteries in hybrid systems with offshore wind generation, diesel and photovoltaic generation, is proposed by [56]. Other studies [49,53] propose the use of SMES in order to perform the task of fluct[illegible]uppression, [illegible]iding storage at the PCC of the wind far[illegible]o the network.

3.2. [illegible]ow voltage [illegible]e through (LVRT)

Th[illegible]ntrol of wind power plants at the point of connection with the external grid during voltage dips, is carried out in order [illegible]ent the wind power plant from being disconnected, which [illegible]se the collapse of the network. For this reason, grid codes require wind power plants to withstand voltage dips up to 0% of the rated voltage and for a specified duration. Therefore, energy storage is not necessary in these situations, but may protect the dc-link of the converters from over-voltage. As in the case of fluctuation suppression service, the suitable storage systems for this application present high ramp-up rates enabling a fast power modulation. Therefore, batteries, flow batteries, and short time scale energy storage like super capacitors, flywheels and SMES are well suited for this application. This article deals with the SMES implementation in a system with fixed speed wind turbines equipped with pitch control. The SMES is connected to an ac cable through a six pulse PWM rectifier/inverter, using IGBTs and two quadrant dc–dc choppers. Both converters are linked by a dc-link capacitor. The improvement of the voltage stability with SMES under LVRT situations is discussed also in [55]. Another C-PCS of SMES is presented in [54]. SMES and super capacitors, batteries and flow batteries are also proposed for LVRT applications.

3.3. Voltage control support

Wind turbines driving a DFIG or full power converters synchronous generators are ways to transfer all or a part of power generated to the network via power converters. With these topologies, the reactive power control of wind generators and hence the voltage control at their connection point is feasible. Also, with the inclusion of energy storage support, the dynamics of the voltage control can be improved. Batteries, flow batteries, and short time scale energy storage like super capacitors, flywheels and SMES, are well suited for this application, mainly because of their high enough ramp rates. Since the storage device must be able to manage both active and reactive power, the C-PCS of the storage device becomes essential. In this sense, FACTS/ESS systems are proposed to carry out this task properly, e.g., [57]

proposes a Distribution Static Synchronous Compensator (DSTATCOM), coupled with a flywheel in order to mitigate voltage stability problems due to the introduction of wind generation in the electric system [77]. Since the dc-link of the STATCOM is strengthened by the energy storage support, it can exchange both active and reactive power. In [62], a STATCOM/BESS is connected to a wind self-excited induction generator, not only to manage reactive power but also to compensate harmonic currents and load changes of an isolated system. As a result, the efficiency and the availability of the system are enhanced. It is important to note that active power control features depend on the storage technology. In this sense, a SMES system presents very good characteristics for a fast injection or absorption of active power.

3.4. Oscillation damping

Wind turbines will be required to mitigate power oscillations of the system by absorbing or injecting active power at frequencies of 0.5–1 Hz [26]. Many storage technologies are suitable for this service. The time of injection/absorption of active power by the storage device is about one minute, therefore, high ramp-up rates and response time are preferable. Thus, HESS, flow batteries, batteries, and short time scale energy storage like super capacitors, flywheels and SMES are well suited for this application. System stability aspects are usually deal with by modal and frequency domain analysis. Flywheels are proposed to be included in the network in favor of better dynamic performance under disturbances [64,65]. The SMES system capacity to quickly manage large quantities of active and reactive power simultaneously is investigated in [60,61,63]. Wind power plants with SMES are required to provide oscillation damping of power in an interconnected system in these studies. A frequency domain analysis, based on linearized system models using eigenvalue techniques, as well as time domain analysis, based on a more detailed non-linear system models under disturbance conditions are proposed. Since system uncertainties must be taken into account, e.g., various generating and load conditions, parameter variations and non-linearities, the application of linear controllers is not always appropriate. In this regard, it is interesting to note the methods described in [63]. The consideration of uncertainties of the system in SMES control provides a much adequate behavior of its response.

3.5. Spinning reserve

According to [34], spinning reserve is defined as the unused capacity that can be activated by the system operator's decision, and which is provided by synchronizing with the network devices capable of affecting the active power of the system. There are many storage technologies which are suitable for this application: flywheels, SMES, batteries, flow batteries, HESS, CAES or PHS installations. Batteries and flow batteries have been the subject of study in numerous publications for providing spinning reserve capability in wind power plants. The provision of spinning reserves plays a key role, especially in isolated systems [34]. In this sense, BESS is proposed to be included in an isolated wind–hydro–gas system in [34]. It is important to remark that wind generator power oscillations for a period of 30 min are reduced by a factor of 3. Flow batteries in spinning reserve applications have been extensively reported in literature.

3.6. Load following

In this service, storage systems are required to provide energy in the time frame of minutes to 10 h [29]. Due to the stochastic nature of wind, the wind power plant output would not match the power demand. In this sense, the ESS can be used to store and inject electrical power for hours. Batteries, flow batteries, as well as HESS, CAES or PHS installations are well suited for this application. Probably, a glaring example of the feasibility of combining wind with battery solutions is a wind power installation case in Futumata (Japan), where a 34 MW NaS battery bank is used to level the production of a 51 MW wind power plant. In this case, control and dimensioning aspects of flow batteries are discussed in [69,71]. As a conclusion of these works, it can be said that many techno-economic benefits for the electrical system derive from a proper solution of these aspects. As an example, [68] presents a stochastic electricity market model in order to study the effects of high penetration of wind power in the electrical systems, as well as the economical viability of including CAES solutions. Finally, it is important to remark that hydrogen-based storage technologies are considered as one of the most promising technologies in load following applications. Actually, several demo projects have been developed as a proof of concept concerning stand-alone systems with wind, photovoltaic generation and hydrogen storage [66,67].

3.7. Peak shaving

This service is within the time frame of 1–10 h. The operating strategy for the storage devices is to store cheap energy at off-peak demand periods (overnight), and to inject it into the network during periods of high electricity demand, and hence soften the typical mountain and valley shape of the load curve [70]. Well suited ESSs for peak shaving applications are batteries, flow batteries, CAES, HESS and PHS. Regarding the batteries, numerous techno-economic studies display the feasibility to store energy during off-peak demand hours and sell it at peak demand periods. Without any doubt, PHS [73,79] is considered to be one of the most well suited storage systems in order to achieve high penetration levels of wind power in isolated systems. In addition, a significant reduction of CO_2 emissions results from the use of PHS installations instead of using fuel peak power plants.

3.8. Transmission curtailment

In this application, storage technologies are required to provide energy in the time frame of 5–12 h. Due to several reasons, such as the need for ensuring the stability of the electrical system or technical limitations in power transmission lines, wind power plants have to be disconnected. In this sense, an ESS can store energy for hours and inject it in a controlled manner according to the capacity of transmission lines and stability issues, and thus, avoiding the disconnection of wind turbines. Well suited ESS for this application is flow batteries, CAES, hydrogen-based systems and PHS installations [76]. Once the hydrogen is stored, it can be used in different ways: either to generate electricity in fuel cells and inject it into the network during periods of peak power demand, or to use in other areas, such as the field of mobility.

3.9. Time shifting

In time shifting services, storage systems are required to provide energy in the time frame of 5–12 h. In this case, ESS is required to absorb all the energy from wind power plants during off-peak demand periods, supplemented with cheap power bought from the network if necessary, and selling it during peak power demand periods, thus avoiding the activation or update of other conventional peak power generation plants. Flow batteries, CAES, PHS installations and hydrogen-based storage technologies are well suited for this application. In [67], the effects on the operation of electrical networks considering bulk energy storage capacity and wind power plants are discussed. In this sense, many

operating strategies for wind-ESS are considered. One of the most interesting case studies is based on charging the storage device continuously for 12 h period (low demand period) and injecting its power in a controlled manner during the following 12 h (high demand period). As a conclusion, the fact is highlighted that time shifting services by means of ESS inclusion into the network are not economically viable without any kind of subsidy, due to high investments costs of the technologies (in this case, CAES systems is the most favorable system) and relatively low energy efficiencies (depending on the system). Regarding environmental aspects, ESS should be able to inject power during the entire high peak demand period; otherwise, the operation of base load plants would be increased, with a consequent increase of CO_2 emissions.

3.10. Unit commitment

In unit commitment services, storage systems are required to provide energy in the time-frame of hours to days. Due to the uncertainties regarding mesoscale variations of the wind, it is hard to manage the commitment of wind turbines in order to meet the estimated demand at all times. Also, the introduction of wind power plants into electrical systems motivates the need to maintain a certain level of energy reserves in order to compensate forecast errors. Therefore, the introduction of high capability ESS into the network may be useful to fight the effects of uncertainties in wind forecasting and to reduce system energy reserves during its normal operation. Large scale energy storage systems are suitable for this application: CAES and PHS installations, as well as hydrogen-based storage technologies. This topic is addressed as a numerical optimization problem, in which the objective function is to minimize the operation costs of the electrical network, so as to maximize the return of the investments in including ESS [34]. For instance, the unit commitment problem is formulated in a power system with wind generation and CAES [74]. The benefits of including CAES installations in order to reduce the operation costs of the electrical network by means of allowing the use of wind energy in charging the storage systems are discussed. Meanwhile, when the energy is not required by the system, the disconnection of the wind turbines occurs.

3.11. Seasonal storage

In this application, ESS capable of storing and injecting energy during periods in the time frame of months are well suited. Storing energy for long periods of time can be useful in systems with large seasonal variations in the level of generation or consumption. Clearly, only the storage technologies with a very large energy capacity and no self-discharge are eligible, such as large PHS installations or hydrogen-based solutions. In cases where it can be economically interesting to include seasonal storage, and taking into account the investment costs regarding the installation of wind turbines and storage systems based on hydrogen, it may look favorable to oversize wind power plants in order to reduce the size of the storage reserves [75]. However, this would increase the non-utilized wind power capacity range and hence decrease the efficiency of the system. On the other hand, the energy costs of the system would be reduced. A demo project regarding seasonal storage by means of hydrogen-based storage technologies in a stand-alone system is described in [67]. It must be noted that although storing energy during long periods of time is technically feasible due to no leaks in the hydrogen storage tank. The use of the RFC must also be limited in order to store the excess productions of wind power, in favor of minimizing the losses of the system, since the energy efficiency of RFCs is very low.

4. Conclusions

In this paper, the operating principles as well as the main characteristics of several storage technologies suitable for stationary applications have been described. In addition, a summary of potential ESS applications in wind power have been defined and discussed according to an extensive literature review. In conclusion, it is worth pointing out that the operation of the power system through wind power plants can have several benefits:

- High power ramp rates of some systems such as SMES, flywheels or super-capacitors allow their use for power smoothing of wind turbines, favoring the mitigation of the voltage and frequency variations at the connection point of the wind power plant.
- Regarding the use of short-time-scale storage technologies, their optimal location in the wind plant and sizing have to be addressed in order to ensure the proper operation. In addition, since the CPCS of the ESS have to interact with the power converters of wind turbines in most of the cases, the topology of the wind plant, as well as the wind turbine types and control strategies play a key role in the system operation and design.
- Other aspects related with the system stability under perturbations, like oscillation damping issues and LVRT capability, become clearly improved with energy storage support. These capabilities take on a key role from their incorporation into grid codes. Once more, energy technologies with high ramp rates are required.
- The technical feasibility of isolated and hybrid systems with high penetration rates of wind power become significantly improved, since the predictability of wind power plants with ESS is increased. Also, a continuous power supply for the loads of such systems can be ensured.
- The predictability improvement of the output of wind power plants with an ESS not only involves technical benefits that favor the incorporation of wind power in the network, but also economic benefits owing to the penalty reductions in forecasting errors. In addition, operation costs of the power system can be reduced due to the reduced power reserve requirements of the system.
- The installation of ESS strongly depends on the economic viability of the project. In this sense, although hydrogen-based storage technologies have a great potential for long term storage applications, the main challenges for their inclusion are related to the uncertainty of their economic viability (due to high system costs and low energy efficiency) and the dependence on high hydrogen market prices.
- A proper control strategy by the system operator is necessary in order to ensure the correctness in the utilization of long term storage systems. In addition, it is found that ESS operators should receive subsidies according to the emissions that would imply the use of conventional fuel plants for peak shaving applications, in order to make their use economically profitable.
- Nowadays, there is a tremendous effort in improving the capabilities and efficiencies of the available storage systems, as well as reducing their capital costs. The aim of this research is to make ESS economically suitable for the use in stationary applications and, therefore, allow higher penetration ratios of renewable energies in the power system.

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